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AUTOMATED DESIGN OF COUPLED RF CAVITIES USING 2-D AND 3-D CODES *

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Abstract

Coupled RF cavities in the Accelerator Production of Tritium Project have been designed using a procedure in which a 2-D code (CCT) searches for a design that meets frequency and coupling requirements, while a 3-D code (HFSS) is used to obtain empirical factors used by CCT to characterize the coupling slot between cavities. Using assumed values of the empirical factors, CCT runs the Superfish code iteratively to solve for a trial cavity design that has a specified frequency and coupling. The frequency shifts and the coupling constant k of the slot are modeled in CCT using a perturbation theory, the results of which are adjusted using the empirical factors. Given a trial design, HFSS is run using periodic boundary conditions to obtain a mode spectrum. The mode spectrum is processed using the DISPER code to obtain values of the coupling and the frequencies with slots. These results are used to calculate a new set of empirical factors, which are fed back into CCT for another design iteration. Cold models have been fabricated and tested to validate the codes, and results will be presented.

1 CCT – 2-D METHOD

1.1 The CCT Code

The function of the CCT (Coupled Cavity Tuning) code [1] is to solve for the dimensions of the accelerating cavity (AC), the coupling cavity (CC), and the distance between the AC and CC, such that the structure achieves design frequencies and coupling, k. CCT obtains a self-consistent solution in which the structure is tuned to the design frequencies and the effects of the coupling slot between the AC and CC are taken into account.

The CCT code controls the 2-D axisymmetric code, CCLFISH [2]. CCLFISH performs RF calculations for a cavity without a slot and tunes the cavity to a target frequency, which accounts for the frequency shift caused by the slot. The effects of the slot are modeled in CCT by means of semi-empirical equations, given below.

1.2 Semi-empirical Equations for Slot Effects

The effects of the coupling slot are based on theoretical approaches of Gao [3] and Greninger [4], which, are based on the Slater perturbation theory. The theoretical equations are adjusted by empirical factors [1]. The functional form of the equations is given below.

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The coupling coefficient k between an AC and a CC that are coupled by an elliptical slot is given by:

$$k = A_k f_1(W, L, t, E_{ac}, E_{cc}, U_{ac}, U_{cc}) \tag{1}$$

where A_k is an empirical correction factor, W, L, and t are the full width, full length, and thickness respectively of the slot, E and H are electric field and magnetic field in a particular cavity (AC or CC) evaluated at a location central to the slot, and U is the stored energy in the cavity.

The frequency shifts for the AC and CC caused by the slot are given by

$$\Delta f_{ac} = A_{fac} f_2(W, L, t, E_{ac}, U_{ac}) \tag{2}$$

$$\Delta f_{cc} = A_{fcc} f_2(W, L, t, E_{cc}, U_{cc}) \tag{3}$$

where A_{fac} and A_{fcc} are empirical factors.

The next-nearest neighbor coupling coefficient, kk, between two adjacent AC's, is given by

$$kk = A_{kk} f_3(W, L, t, |x|, E_{ac}, E_{cc}, U_{ac}, U_{cc}) \tag{4}$$

where A_{kk} is an empirical factor, and $|x|$ is the distance between the centers of two adjacent slots in the CC.

The accelerating $\pi/2$ mode frequency for the structure is the net frequency of the AC adjusted for the effects of the slot and next-nearest-neighbor coupling, given by

$$f_{\pi/2} = \frac{f_{fish} - \Delta f_{mesh} - \Delta f_{ac}}{\sqrt{1 - kk}} \tag{5}$$

where f_{fish} is the frequency calculated by CCLFISH, Δf_{mesh} is a correction for finite mesh, and Δf_{ac} is the frequency shift caused by the slot (Eq. 2). A similar equation, with kk = 0, is used to calculate the net frequency of the coupling cavity.

In Eq. (1-4), four empirical "A" factors account for the coupling slot. These factors may be determined from cold model data, or they may be calculated from a three-dimensional analysis, avoiding the cost of cold models.

1.3 CCT logic

CCT calculates a self-consistent solution using the following logic:

1. Guess at values for the tunable cavity dimensions.
2. Assume values of the cavity frequency shifts.
3. Using these frequency shifts, calculate the shifted CCLFISH target frequencies, f_{SF} from Eq. (5).
4. Run CCLFISH to tune the AC and CC to meet the shifted target frequencies, updating the dimensions.

5. Assume a distance between the AC and CC.
6. Calculate the geometry of the coupling slot.
7. Calculate the coupling coefficients k and kk.
8. Compare the calculated k with the design target k. If not converged, adjust guess at the cavity distance and go to Step 6.
9. Calculate new frequency shifts. If the frequency shifts have not converged, go to Step 3.

2 HFSS – 3-D METHOD

2.1 Calculation of Modes and Dispersion Diagram using HFSS

Because of meshing problems with the 3-D code HFSS, the accuracy of its calculated mode frequencies is insufficient for design purposes. The 2-D code Superfish [2] is sufficiently accurate, but it cannot account for the slot. By combining the two codes, one can have the best of both. It has been demonstrated that the accuracy of the *frequency shifts* calculated by HFSS due to coupling slots and slot chamfers is sufficient for design purposes. In addition, the shape of the dispersion diagram calculated by HFSS is predicted well enough that it can be used to extract nearest and next-nearest neighbor coupling constants with accuracy sufficient for design.

The following procedure is used to calculate the needed cavity frequencies and dispersion diagrams:

- Models are constructed of: ½ the accelerating cavity, ¼ coupling cavity without vacuum port, ¼ coupling cavity with vacuum port, and the coupled system consisting of ½ accelerating cavity coupled to two ¼ models of the coupling cavity with vacuum port. Models are segmented to guide the automatic meshing in HFSS. The same segmentation is used in the uncoupled models as in the coupled system.
- The frequencies of the uncoupled cavities, without slots, are calculated.
- The mode frequencies of the coupled system are calculated by applying periodic boundary conditions to the end symmetry planes of the ¼ coupling cavities, simulating the modes of an infinite biperiodic structure. Phase shifts of 0^0, 90^0, and 180^0 are applied between the boundaries. The modes are plotted as a dispersion diagram (frequency vs. phase).

2.2 Evaluation of Empirical Factors for CCT

The dispersion diagram is represented numerically as a finite set of points. A curve fitting program, DISPER, is used to fit a theoretical dispersion diagram of a biperiodic structure to these points. There are enough points on the dispersion diagram for use in extracting individual cavity frequencies (including slot), nearest neighbor coupling constants, and next-nearest neighbor coupling constants.

The frequencies and other parameters calculated by HFSS and extracted from the dispersion diagram are listed below:

f_{0ahfss}	HFSS accelerating cavity frequency, no coupling slot.
$f_{0cchfss}$	HFSS coupling cavity frequency, no vacuum port, no slot.
$f_{0ccvphfss}$	HFSS coupling cavity frequency with vacuum port, no slot.
f_{ahfss}	Accelerating cavity frequency with slot
$f_{ccvphfss}$	Coupling cavity frequency with slot
k	Nearest neighbor coupling constant, accelerating cavity to coupling cavity.
kk	Next-nearest neighbor coupling constant, accelerating cavity to accelerating cavity.

The CCT A factors are determined from:

$$\Delta f_{achfss} = f_{0ahfss} - f_{ahfss} = A_{fac} f_2$$

$$\Delta f_{cchfss} = f_{0ccvphfss} - f_{ccvphfss} = A_{fcc} f_2$$

$$k = A_k f_1$$

$$kk = A_{kk} f_3,$$

Where f_1 through f_3 are defined by Eqs. (1-4).

3 EXAMPLE OF CAVITY DESIGN

This technique was applied to the design of a cold model for CCL segment 283 of APT, a cold model that had already been built and tested. For this design, we had no comparable data with which to construct A factors. Trial A factors were derived from earlier cold model tests of SNS cavities. Using these A factors, CCT was used to calculate the geometry of the segment 283 cold model. The model was fabricated, tuned, and tested. As expected, the results did not exactly match the goals, but they were close.

A redesign of this cold model to the original objectives, using the combined 2-D/3-D method described here, would produce a different geometry with no experimental basis to check it. Instead, the design objectives for this exercise were modified to reflect the experimental frequencies and coupling actually measured. In this way, we can validate the 2-D/3-D approach by reproducing (a) the original design geometry and (b) the modified set of A factors that were determined experimentally.

3.1 Initial Designs Using CCT Alone

The original design objectives of the segment 283 cold model were to achieve a coupling of 5% and a $\pi/2$ mode frequency of 700 MHz after the slot was chamfered and the tuning was complete. The original cavity dimensions were calculated with CCT using the A factors derived from SNS data. The parameters are listed later in Table 1.

For the 2-D/3-D design exercise reported here, the state of the as-built cold model is taken to be after the coupling slot chamfer was cut but before the tuning rings and CC posts were trimmed for the final tuning. In this state, the following measurements were obtained using DISPER fits to the measured mode spectra:

$f_{\pi/2}$ = 701.468 MHz
f_1 (AC frequency with slot) = 703.612 MHz
f_2 (CC frequency with slot) = 695.464 MHz
k = .04836
kk = –.00651

$f_{\pi/2}$ = 701.468 MHz and k = .04836 are the main design objectives in this exercise. Also, the objective of f_2 was set to 695.464 MHz, but the effect of the vacuum port in the CC was ignored. This assumption has negligible effect on the conclusions, as errors in CC frequency are compensated by trimming the CC posts, and they do not affect any other design parameters. The dimensions obtained with CCT are listed in Table 1.

3.2 Design Iteration Using CCT and HFSS

The following tables show the results of iterating between the 2-D code CCT and the 3-D code HFSS. Table 1 shows the segment 283 cold model design parameters for the chamfered, un-tuned state. Designs listed include the initial design, derived from the SNS A factors, and the sequence of 2-D/3-D design iterations, in which the target was changed which reflect measured frequency and coupling.

Table 1: Iteration of 283 Cavity Design Parameters

Design condition	Initial design	Rev. target 1	Rev. target 2	Rev. target 3
A factors used	SNS	SNS	HFSS 1	HFSS 2
$\pi/2$ frequency	701.849	701.468	701.468	701.468
k, coupling	.04843	.04836	.04836	.04836
Δf_{ac}	11.477	11.341	11.562	11.542
Δf_{cc}	21.490	22.161	22.395	22.426
kk, NNN coupl.	–.00665	–.00525	–.00616	–.00635
AC diam. (in.)	11.310	11.328	11.318	11.317
CC diam. (in.)	7.635	7.647	7.639	7.639
AC-CC distance	8.321	8.344	8.338	8.337

In the last three columns, beginning with an assumed set of A factors, the 2-D/3-D iteration converges to a new set of A factors, obtained with HFSS entirely by calculations, that do not depend on experimental data. When the cavities are designed by this method the geometry converges close to a configuration that, experimentally, produces the observed frequency and coupling.

3.3 Converged Design vs. Experiment

Table 2 shows a comparison of the converged design calculations and the experimental data itself. In this case, one would expect the values of the $\pi/2$ frequency, k, and f_2 to be identical because CCT reproduces the target design conditions. The more interesting parameters to compare are the derived values of f_1, and kk.

Table 2: Converged HFSS / CCT Design vs. Experiment

Parameter	HFSS calcs	CCT design calcs	Exper. data
$\pi/2$ frequency	703.881	701.468	701.468
k, coupling coeff.	.04830	.04836	.04836
f_1 (AC freq w/ slot)	706.106	703.690	703.612
kk, NNN coupling	-.00633	–.00634	–.00651

The agreement of f_1, and kk between CCT and experiment is good. Using A factors generated solely by HFSS, the coupling slot is represented accurately by CCT.

4 CONCLUSIONS

The iteration between 2-D (CCT) and 3-D (HFSS) calculations provides a design equivalent to one in which 3-D calculations are used to model the slot rather than empirical correlations, but the iterations are much faster. The absolute frequencies calculated by HFSS are in error, but the frequency differences are accurate. The frequencies calculated by CCT and CCLFISH, with empirical corrections for the slot effects, are well within the tuning range. Using this approach, one can avoid the cost and time of most cold models, and reserve cold models for code validation with different cavity types.

5 REFERENCES

[1] P. D. Smith, "CCT, a Code to Automate the Design Of Coupled Cavities," presented at the XX International LINAC Conference, Monterey. CA, Aug 21-25, 2000, Los Alamos National Laboratory report LA-UR-00-3504.

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